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Variation of the southward interior flow of the North Pacific subtropical gyre, as revealed by a repeat hydrographic survey

Keywords: North Pacific, Subtropical gyre, Interior region, Volume transport, Volume transport-averaged temperature

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Abstract

Baroclinic variations of the southward flow in the interior region of the North Pacific subtropical gyre are presented with five hydrographic sections from San Francisco to near Japan during 2004–2006. The volume transport-averaged temperature of the interior flow, which varies vigorously in the range of 0.8°C, is negatively correlated with the transport in the density layer of 24.5–26.5σ_θ, associated with the vertical current structure changes. The transport variation in the density layer is thus mainly responsible for the thermal impact of the interior flow on the heat transport of the subtropical gyre.

1 Introduction

The subtropical gyre of the North Pacific transports considerable amount of heat from the tropical region to the mid-latitude region. Since its net meridional heat transport is considered to play a critical role in the global climate system, many investigators have conducted its estimation in past (Bryden and Imawaki, 2001; Nagano et al., 2009, 2010). To estimate the net heat transport of the subtropical gyre, volume transport-averaged temperatures of currents involved in the gyre have been frequently used in past studies such as Nagano et al. (2009, 2010); thus, the volume transport-averaged temperatures are essential indices to evaluate the thermal impacts of the current variations on the climate.

Except the region of the northeastward flowing western boundary current, so-called the Kuroshio, most part of the subtropical gyre is occupied with the southward flow. The southward interior flow constitutes the return flow of the Kuroshio, i.e., the western boundary current of the North Pacific subtropical gyre. The volume transport-averaged temperature in the interior region, T_I, is lower than that of the Kuroshio due to the intensive heat loss from the sea surface in the Kuroshio Extension region, east of Japan. In comparison with the volume transport-averaged temperature of the Kuroshio, T_{I} has not been studied intensively because of too long ship time necessary for and then rare occasions of trans-Pacific observations.

A trans-Pacific hydrographic section of the World Ocean Circulation Experiment (WOCE) P02, at the latitude of 30°N, was obtained in parts by two cruises in October 1993 and January 1994. From this data, Bryden and Imawaki (2001) calculated T_{I} to be 15.8°C. From another data of the P02 observation in June–August 2004, Nagano et al. (2009) calculated T_{I} to be 15.4°C. Taking into account of the variations of the volume transport and the volume transport-averaged temperature of the Kuroshio, Nagano et al. (2010) calculated the meridional heat transport of the subtropical gyre to be 0.19–0.22 PW (1 PW = 10^{15} W) by the use of 15.4°C as T_{I}. Nagano et al. (2010) noted that the use of 15.8°C instead of 15.4°C reduces about 20% of the net heat transport of the gyre. Thus, only such an overestimation of T_{I} results in a significant underestimation of the net heat transport of the subtropical gyre.

Because of insufficient knowledge on the variation of T_{I}, Bryden and Imawaki (2001) and Nagano et al. (2009, 2010) assumed T_{I} to be constant. For more accurate estimation of the heat transport, we should examine the variability of the flow and thermal structures which are associated with the variation of T_{I}. By using expendable bathythermograph (XBT) and/or conductivity-temperature-depth (XCTD) probes, repeat high-resolution XBT/XCTD (HRX) data have been collected along cruise tracks of voluntary ships in the North Pacific (e.g., Roemmich et al., 2001; Uehara et al., 2008) and other oceans. The HRX data can supplement the trans-Pacific data at the WOCE hydrographic lines such as P02, and the analysis of the HRX data is expected to reveal the variations of the flow and thermal structures in the interior region of the subtropical gyre.

In this paper, we calculated T_I from five sets of hydrographic sections from Honolulu (Hawaii) to San Francisco (California) (HRX-PX37) by the M/V *Enterprise* and from Honolulu to Japan (PX40) by the T/V *Miyagi-maru* in June 2004–November 2006 since the five sections were collected almost simultaneously in the interior region of the subtropical gyre.

2 Data

The line of PX40 largely intersects a western part of the interior region of the subtropical gyre at an average latitude of about 29°N (Fig. 1). Detailed information about the cruises along the line of PX40 was provided by Uehara et al. (2008). From 150°E to Japan, the *Miyagi-maru* took the northern or southern routes which were oriented to the ports in Miyagi or Kanagawa prefectures, respectively. The deviations of the cruise tracks in the Kuroshio Extension region may cause large errors of the estimated values of the volume transport and volume transport-averaged temperature due to abrupt and complicated spatial variations of the current there. Thus, we used the data east of 150°E where the tracks deviated less than 3° from the latitude of the mean track and did not intersect the Kuroshio Extension.

Temperature data at PX40 were obtained almost three times a year in March, June, and November down to a depth of about 780 m at the longitudinal interval of 0.5° by XBT T-7 probes (The Tsurumi-Seiki Co., Ltd.) which are rated to 760 m depth. The salinity at each XBT site was estimated from the temperature-salinity relationship at the nearest XCTD site at the longitudinal interval of 5° by XCTD-1 probes (The Tsurumi-Seiki Co., Ltd.) Temperature and salinity values were linearly interpolated at the longitudinal interval of 0.5° (equivalent to ~50 km) and were averaged vertically every 10 m down to the depth of 780 m.

Temperature data at the line of PX37 were obtained by the Scripps High Resolution XBT Program (www-hrx.ucsd.edu). Temperature data were collected by XBT Deep Blue probes

(Sippican Inc.), which are nominally rated to 760 m depth, with a maximum horizontal interval of about 60 km. The data were gridded at the vertical interval of 10 m. In March 2005 and November 2006, temperature sections between Honolulu and San Francisco could be obtained simultaneously with that between Japan and Honolulu, i.e., PX40. The data in Junes of 2004, 2005, and 2006 are based on the data at PX37 which were obtained within two months of the PX40 observations. In total, the five sections from San Francisco to Japan via Honolulu could be obtained during June 2004–November 2006. Salinity at the XBT data points were determined by averaging the Argo float data within a horizontal distance of 150 km from the XBT points in the database maintained by Japan Argo (www.jamstec.go.jp/ARGO/argoweb/argo). The data were interpolated vertically every 10 m down to the depth of 780 m.

To calculate the geostrophic velocity, we set the reference depth to 700 m above the nominal maximum depth of the XBT measurements. This reference depth is located in the layer deeper than the isopycnal depth of $26.5\sigma_\theta$ (kg m^{-3}), i.e., in the lower part of the main thermocline, providing the baroclinic variation of the geostrophic transport relative to 700 m. The volume transport across the WOCE P02 line east of 150°E with the reference depth of 700 dbar, 29.6 Sv (1 Sv = 10^6 m^3 s^{-1}), was 12 Sv smaller than 41.5 Sv with the reference depth of 1000 dbar. The difference is considered to be of the same order of magnitude as that of the volume transports at PX37 and PX40 between the reference depths of 700 and 1000 m if the data down to the depth of 1000 m had been obtained.

Each transect at PX37 and PX40 was conducted within half a month. Therefore, by integrating the geostrophic velocity and the temperature along the lines, the influence of mesoscale eddies on the volume transport and volume transport-averaged temperature of the southward interior flow would be canceled out except the region around the western end of the line at 150°E.

It should be noted that the error transport caused by eddies around the western artificially fixed end at 150°E is included in the estimated volume transport and volume transport-averaged temperature.

3 Results

In this study, the volume transport-averaged temperature, T, is defined as

$$T = \frac{\int\int \theta\, v \,\mathrm{dxdz}}{\int\int v \,\mathrm{dxdz}}, \tag{1}$$

where v is the geostrophic velocity normal to the observation lines; θ is the potential temperature; and x and z are the coordinates along the observation line and vertical axis, respectively. The temperatures, T and θ, are in the same unit, °C.

By performing the integrations in Eq. (1) over the whole section from Honolulu to San Francisco (PX37) and to 150°E (PX40) above the depth of 700 m, the volume transport-averaged temperature of the baroclinic flow, T_I, were obtained in Table 1. The values of T_I at PX37 and PX40 are significantly lower than 15.5°C estimated from the P02 line section northward of PX37 and PX40 with the reference depth of 700 dbar. Moreover, it should be noted that the volume transport-averaged temperatures would strongly depend on the adopted reference depth. Using 1000 dbar instead of 700 dbar as the reference depth, the volume transport-averaged temperature at the P02 line is 1°C lower than that with the reference depth of 700 dbar. Accordingly, the estimated T_I from PX37 and PX40 data would have such an order of bias due to the southerly track via Honolulu and the constraint of no motion at 700 m, so that we should focus not on the absolute values but on the relative values.

The maximum and minimum values of T_I were observed to be 14.7°C (November 2006) and 13.9°C (March 2005) (Table 1), respectively; in other words, the difference of T_I maximizes to

0.8°C. In order to illustrate the variation of the density structure at the PX37 and PX40 lines that yields the variation of T_I, the potential density sections are shown in Fig. 2. Contours of the potential density larger than $25.5\sigma_\theta$ commonly shoal eastward, suggesting that the flow in the interior region is directed southward as a whole. Except for March 2005 in Fig. 2b, the seasonal thermocline can be recognized above the depth of about 200 m along the entire lines. In March 2005, the seasonal thermocline disappeared associated with the outcrop of the isopycnal of $24.5\sigma_\theta$ in the west of 175°W; at this time, T_I was observed to be the minimum value.

Salinity anomalies on potential density surfaces can be well characterized by a parameter, called the spiciness (Veronis, 1972; Jackett and McDougall, 1985; Flament, 2002). Figure 8 prepared by Nagano et al. (2010) shows that the spiciness distributes uniformly on the isopycnal surfaces within the lower part of the main thermocline in the offshore interior region of the subtropical gyre. In this study, the spiciness, π, whose unit is the same as that of the potential density, σ_θ, i.e., kg m^{-3}, was calculated by using the polynomial presented by Flament (2002) (Fig. 3). In the interior region of the subtropical gyre, contours of the spiciness are largely flat in the layer between 23.5 and $26.5\sigma_\theta$ as reported by Nagano et al. (2010), although the contours undulate in the eastern part.

Along the west coast of North America, the low-salinity water of subpolar origin, called the shallow salinity-minimum water (SSMW), flows southward (Reid, 1973; Yuan and Talley, 1992), but eventually proceeds to the tropical region (Kawabe and Fujio, 2010) as schematically illustrated by dotted curves in Fig. 1. Therefore, the southward transport of the SSMW should be treated as the separated flow transport from the rest interior flow transport of the subtropical gyre. The SSMW was found to be characterized by the subsurface minimum of the spiciness lower than 0.1π (white thick contours) to the east of 135°W, and is distinct from the water occupying the rest interior region.

Identifying the SSMW as the water with the spiciness lower than 0.1π above the isopycnal surface of $26\sigma_\theta$, the volume transport of the water, V_{SSM}, and the volume transport-averaged temperature, T_{SSM}, of the SSMW were evaluated as in Table 2. The variation range of V_{SSM} is quite small in comparison with that of V_{I}, although T_{SSM} is inversely correlated to T_{I} with the coefficient of -0.88. Therefore, the variations of the volume transport and volume transport-averaged temperature of the SSMW is not the principal factor to vary the volume transport-averaged temperature of the southward interior flow.

To reveal another variation of the interior flow that yields the significant variation of T_{I}, the remaining volume transport of the interior flow at the lines of PX37 and PX40 after the removal of the SSMW transport is divided into potential density segments with the interval of $0.25\sigma_\theta$ (Fig. 4). The primary peak of the net southward volume transport is commonly present in the range between 24.5 and $25.5\sigma_\theta$. Compared with November 2006 (Fig. 4c), the distributions of the volume transport in the other periods are concentrated within narrow density layers such as 24.5–$25.0\sigma_\theta$ in March 2005 (Fig. 4a) and 25.0–$25.5\sigma_\theta$ in Junes of 2004–2006 (Fig. 4b). Particularly, in every June, the volume transports are similarly allocated. Meanwhile, the distribution in November 2006 (Fig. 4c) is deviated toward the upper layer above approximately $24.0\sigma_\theta$ with the secondary peak of the southward volume transport between 23.50 and $23.75\sigma_\theta$.

Due to the variation of the volume transport distribution, the net southward transport within the density layer between 24.5 and $26.5\sigma_\theta$ became noticeably smaller in November 2006 than those in the other periods. For neatness sake, the density layer is simply referred to as the mode water layer in this paper because the density range almost includes those adopted to identify the subtropical and central mode waters by Suga and Hanawa (1995) and Suga et al. (1997), respectively. The volume transport in the mode water layer, called V_{M}, occupies over 60% of the volume transport of the interior flow in the top 700 m, i.e., V_{I}, so that V_{M} may be responsible for the variation of T_{I}. In the shallow layer above $24.5\sigma_\theta$, the southward volume transport is at least up to approximately 5 Sv in November 2006.

The variation range of the volume transport in the mode water layer, V_{M}, (Table 2) is comparable to that of V_{I} (Table 1). Moreover, V_{M} was found to be strongly related to the volume transport-averaged temperature, T_{I}. As plotted in Fig. 5a, obviously, T_{I} and V_{M} are inversely correlated; the correlation coefficient is -0.95. In other words, the higher proportion of the water flowing in the mode water layer yields the lower T_{I}. Thus, the volume transport in the mode water layer is principally responsible for the variation of T_{I} and a potential element affecting the climate through the net heat transport of the subtropical gyre. Meanwhile, the volume transport-averaged temperature in the mode water layer, T_{M}, is less responsible for the variation of T_{I} than V_{M}, as indicated by the negative correlation coefficient of -0.71 (Fig. 5b).

4 Discussion

We estimated the volume transport and volume transport-averaged temperature of the southward interior flow of the North Pacific subtropical gyre on the basis of the five sections from San Francisco to 150°E via Honolulu with the reference depth of 700 m. The volume transport-averaged temperature, T_{I}, strongly depends on the depth of the reference level, but the obtained values was found to vary with the maximum difference of 0.8°C between November 2006 and March 2005 if the reference depth was fixed to 700 m in all cases. The significant variation of T_{I} was demonstrated to be associated with that of volume transport in the density layer between 24.5 and $26.5\sigma_\theta$, i.e., in the mode water layer. The variation of the volume transport in the density layer is accompanied by the vertical distribution change of the transport. Although, due to the limited vertical range by XBT T-7 and Deep Blue, the absolute values of the volume transport and volume transport-averaged temperature were not fully discussed, the PX37 and PX40 data could supplement the knowledge based on the WOCE P02 data.

In this study, the volume transport-averaged temperature of the southward interior flow, which has been treated as an invariable parameter in past studies, was elucidated to vary vigorously. Yet, the characteristics of the temporal variation were not clarified sufficiently due to the sparse data in time. The temporal variation should be more addressed in future works by using data obtained more densely in time. The high-resolution hydrographic observations in the interior region such as along the lines of PX37 and PX40 must be continued for more quantitative investigations with a longer duration and more frequent collections per year.

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Table 1: Volume transport, V_{I}, and the volume transport-averaged temperature, T_{I}, between 150°E and San Francisco. Positive transports are directed southward.

Year	Month	V_{I} (Sv)	T_{I} (°C)
2004	Jun	39.5	14.1
2005	Mar	35.6	13.9
	Jun	37.8	14.1
2006	Jun	34.1	14.4
	Nov	29.2	14.7

Table 2: Volume transport, V_{SSM}, and volume transport-averaged temperature, T_{SSM}, of the SSMW; and volume transport, V_{M}, and volume transport-averaged temperature, T_{M}, within the density layer of 24.5–26.5σ_θ, i.e., the mode water layer. Positive transports are directed southward.

Year	Month	V_{SSM} (Sv)	T_{SSM} (°C)	V_{M} (Sv)	T_{M} (°C)
2004	Jun	3.7	9.7	29.8	14.7
2005	Mar	2.6	9.7	32.1	15.4
	Jun	3.0	9.6	29.2	15.0
2006	Jun	2.5	9.1	26.8	14.9
	Nov	2.3	9.3	18.1	14.6

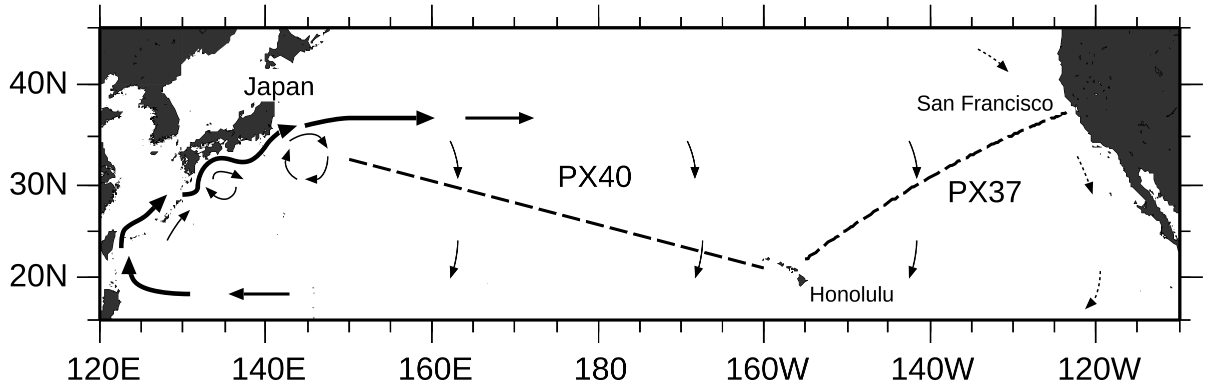

Figure 1: Schematic diagram of the North Pacific subtropical gyre (solid curves with arrows) and flow of the shallow salinity-minimum water (dotted curves with arrows); and the lines of PX37 and PX40 (dashed lines).

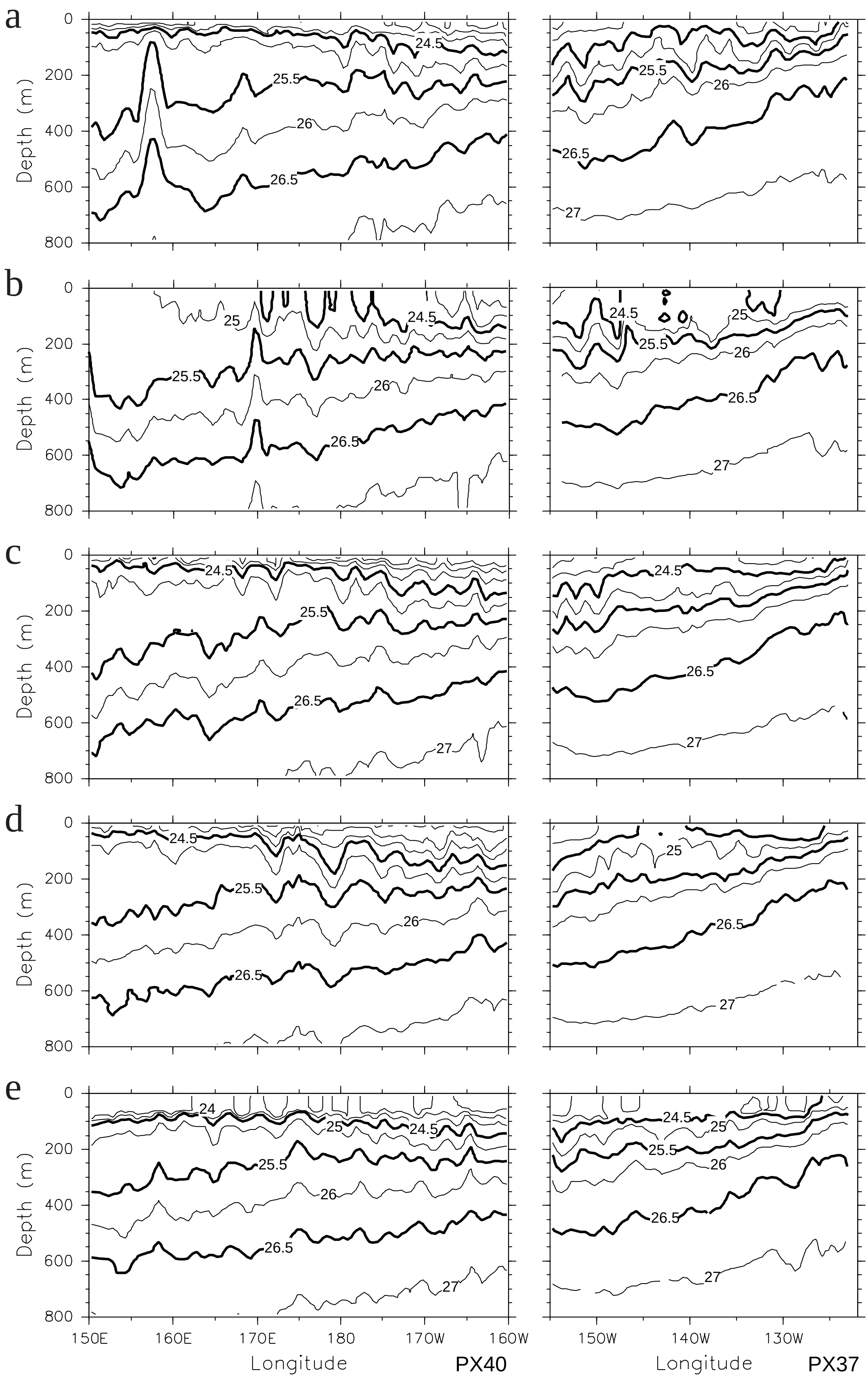

Figure 2: Sections of the potential density σ_θ from San Francisco to 150°E via Honolulu with contour interval of $0.5\sigma_\theta$, thick contours of 24.5, 25.5, and 26.5σ_θ, in (a) June 2004, (b) March 2005, (c) June 2005, (d) June 2006, and (b) November 2006.

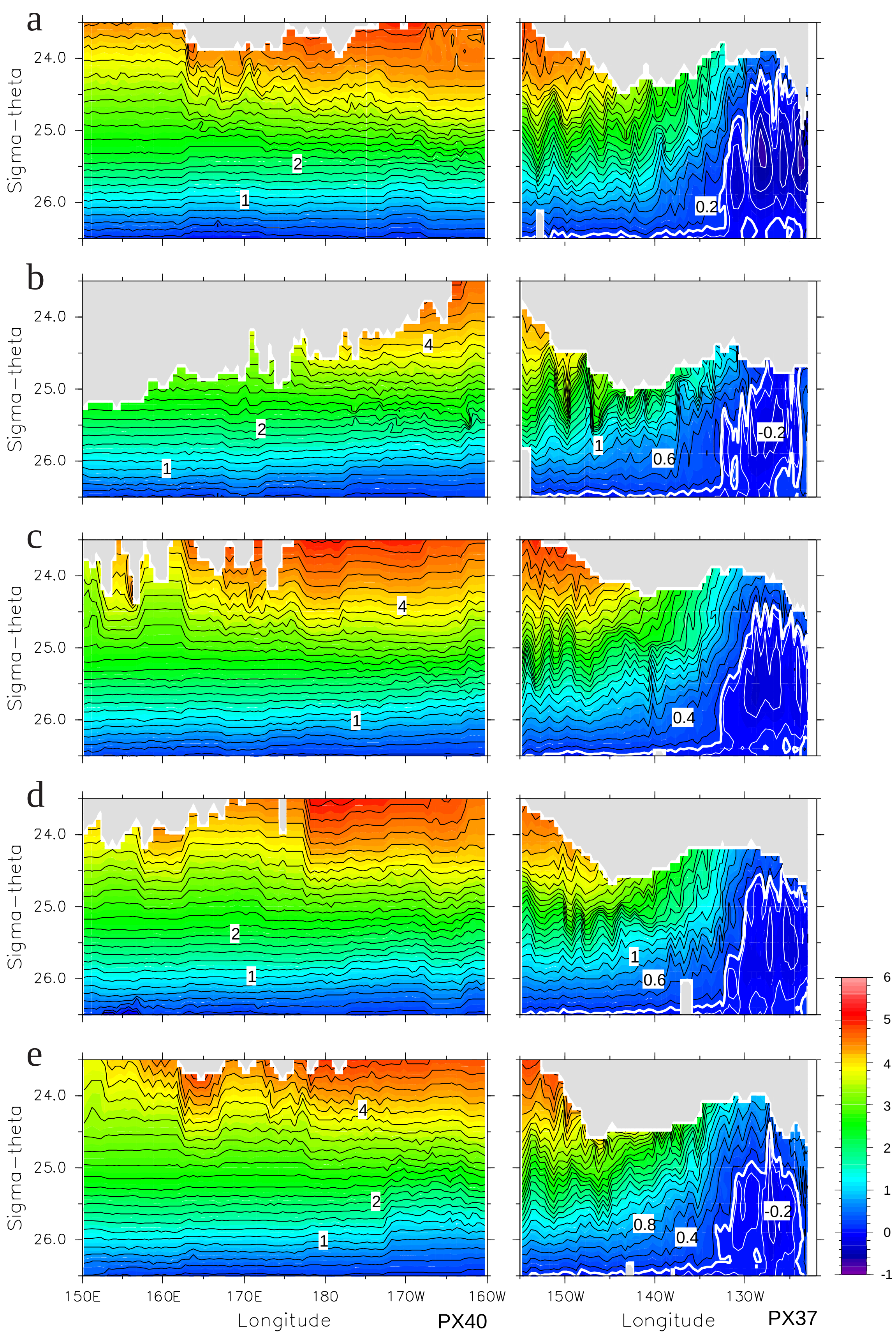

Figure 3: Sections of the spiciness π with respect to the potential density σ_θ from Honolulu to San Francisco (PX37) and to 150°E (PX40) in (a) June 2004, (b) March 2005, (c) June 2005, (d) June 2006, and (b) November 2006. Contour interval is 0.2π and values smaller than 0π is indicated with white thin contours. Only 0.1π is shown with white thick contours.

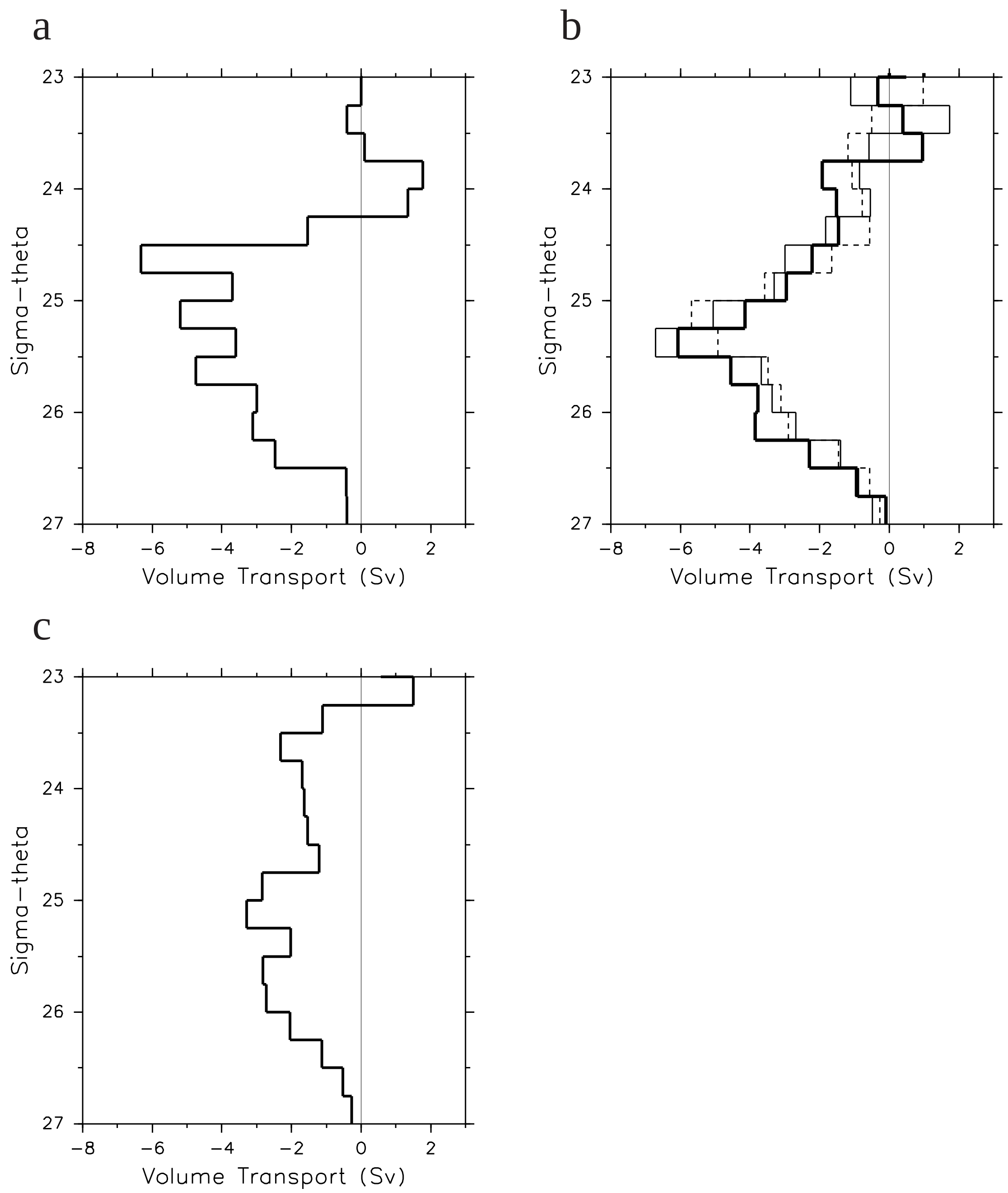

Figure 4: Distributions of the volume transport at the lines of PX37 and PX40 with respect to potential density σ_θ in (a) March 2005, (b) Junes of 2004–2006, and (c) November 2006. Transports were calculated for segments at the interval of $0.25\sigma_\theta$ except the region of the spiciness lower than 0.1π, i.e., the SSMW. Positive values indicate northward volume transports. In (b), values in Junes of 2004, 2005, and 2006 are indicated by thick solid, thin solid, and dashed lines, respectively.

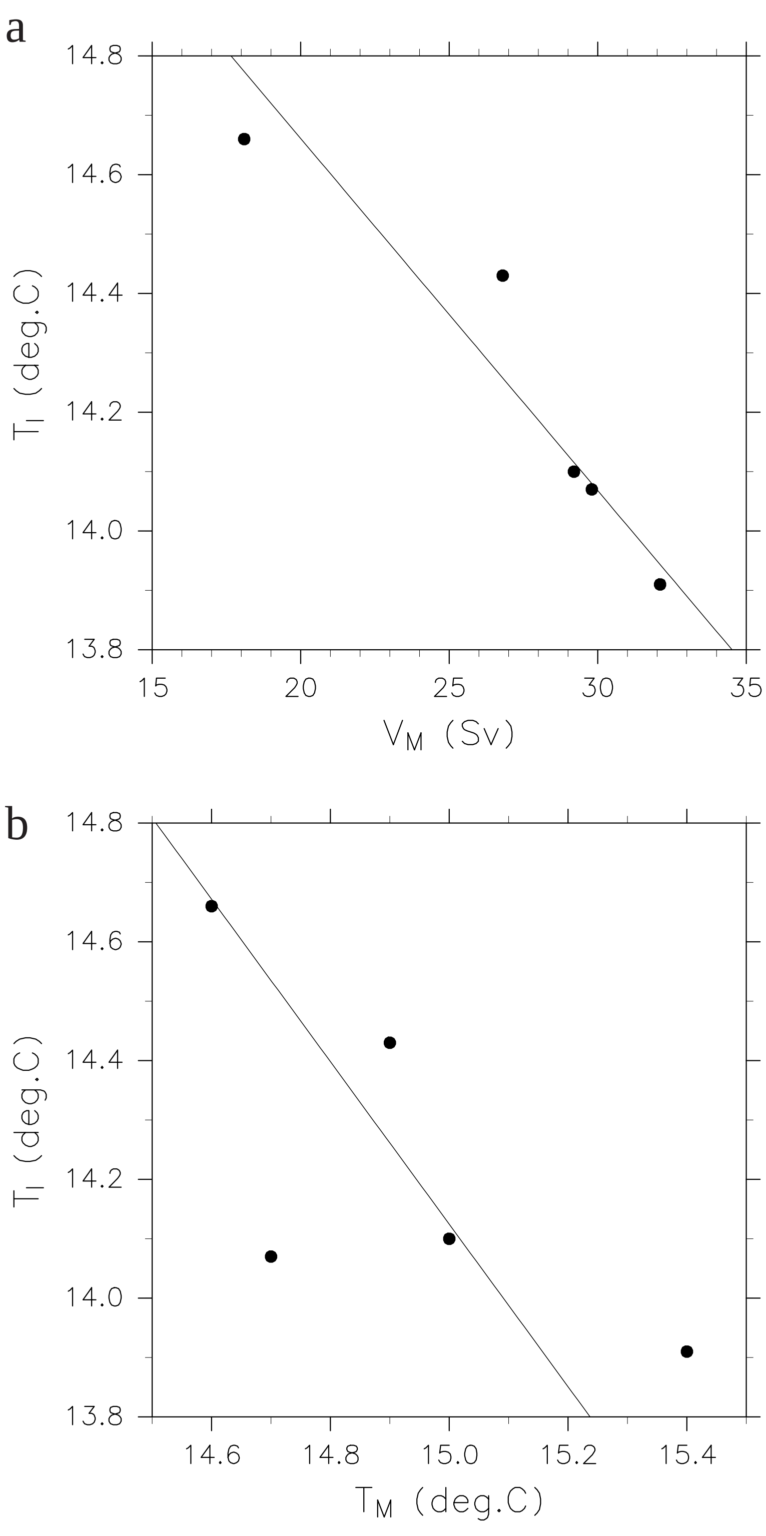

Figure 5: Scatter plots of the volume transport-averaged temperature of the southward interior flow, T_{I}, versus (a) the volume transport, V_{M}, and (b) the volume transport-averaged temperature, T_{M}, for the potential density layer between 24.5 and 26.5σ_θ, i.e., the mode water layer. Slant solid lines are linear regressions.